

UNITED STATES PATENT APPLICATION

FOR

**MEMS BASES OVER-THE-AIR  
OPTICAL DATA TRANSMISSION  
SYSTEM**

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## BACKGROUND OF THE INVENTION

This non-provisional application takes priority from United States Provisional Application Number 60/210,613 filed on June 9, 2001.

A description of some technologies related to embodiments of the invention follows:

US 4,662,004 Fredriksen, et al. Fredriksen describes optical communication link that includes a separate laser (in addition to the data transmission laser), which returns information about the level of the received signal to the transmitter. This separate laser is adjusted to emit power proportional to the received beam power.

US 4,832,402 Brooks. Brooks describes a fast scanning mirror used to time-multiplex light beam into several steering mirrors, each of the steering mirrors aim the beam into one or a group of targets clustered together. The steering mirrors are slow due to the large angle required. Brooks also describes the use of "beacon transmitters" to aid in target tracking (column 9 line 15).

US 5,282,073 Defour, et al. Defour shows optical communications system with two galvanometer mirrors for beam steering, and a complex wide-angle

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lens to increase the angular scanning to a half-sphere. Defour also describes target designation step iterative step of bilateral acquisition and a third step of exchanging data.

**US 5,390,040** Mayeux. Mayeux describes the use of one steer-able mirror at the expanded beam location, for aiming both the transmit beam and receive beam. Part of the surface of the mirror is used for transmission, and another part for reception. (Mayeux calls these parts of the mirror "field of views", in contrast to common terminology).

**US 5,448,391** Iriama, et al. Iriama describes the use of optical Position Detector sensor (common art) to track the beam direction. A pair of mirrors is used for slow, large angle direction control and a fast lens is moved for fast corrections.

**US 5,646,761** Medved, et al. Medved describes here an optical communications between stationary location like an airport gate and a movable object, like an airplane parked at the gate. The optical units on the gate and the airplane are searching for each other and stop this search when aligned.

**US 5,710,652** Bloom, et al. Bloom describes optical transmission equipment to interconnect low Earth orbit satellites. The whole transmitter and

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receiver unit is mounted on gimbals. Two lasers are used, one for tracking and one for data. A CCD optical detector detects the target location for tracking servo control.

US 5,768,923 Doucet, et al. Doucet discloses the distribution of Television signals from one source to many receivers. The transmitter uses X-Y beam deflector made of two galvanometer driven mirrors. This assembly is used to direct the beam into a specific receiver at a selected home.

US 5,818,619 Medved, et al. Medved describes here a communications network with air-links. A converter unit is converting the physical data transmission in the network to electricity, and drives an air-link transmitter. Similarly, the received beam is converted to electricity after reception. Medved also describes an optical switch to have one air-link serving plurality of networks between the same two locations.

EP 962796A2 Application Laor, et al. This application describes MEMS mirror construction.

## SUMMARY OF THE INVENTION

Optical interconnect with light beams between buildings suffers from a difficulty associated with the movement of the buildings. The movements include waving in the wind, environmental vibrations, land shift, earthquakes etc. Common over-the-air optical transmission equipment either uses narrow beam laser transmitters with tracking mechanisms or use LED based wide beam transmitters with fixed aiming.

MEMS is a technology that is used to manufacture small mechanical systems using common Silicon foundry processes. We describe here the use of narrow field of view transmission with MEMS mirror being used to fine tune the beam direction. Since the MEMS mirror is rather small, 1-3 millimeters in diameter, it is difficult, if not impossible to use it to aim the expanded beam. In an embodiment of the invention, the MEMS mirror is installed near the light source, where the beam is small in diameter. This positioning enables only small angular deflection of the beam. The transmission equipment will be aimed coarsely manually or with motors, and the MEMS mirror will do fine aiming with fast response. With course motorized aiming, the motors may be operated to search and find the other side of the communication link. After the MEMS mirror begun aiming the beam, the motors could be adjusted slowly to hold the

aim such that the MEMS mirror average angular deviation is around zero. This will maximize the correction capability of the MEMS mirror.

Note: we will use here "light" for all electromagnetic waves from the ultra-violet to infrared, and not only for the visible spectrum. This is a common use of the term. The common transmission wavelength is with light in the near infrared, and not only for the visible spectrum. This is a common use of the term. The common transmission wavelength is with light in the near infrared between 600 and 1600 nano-meters.

Another feature of the invention is the use of optical fiber to carry light from the light source in the data equipment to the optical beam transmitter on the roof or in a window. Another optical fiber carries the light from the optical beam receiver on the roof or in a window to the detector in the data equipment. This facilitates the changing of data equipment, changing data rates, changing protocols, etc. without the need to replace the optical beam transmitter or beam receiver. The system may be upgraded to carry light in more than one wavelength using the same optical beam transmitter and receiver. For long transmission lengths, an optical fiber amplifier could be installed between the light source and the optical beam transmitter, or between the optical beam receiver and the detector, or both locations. For systems located in areas with

common fog problems, such amplifiers could be set to kick-in when transmission is fading.

Yet another feature is the use of two fast optical fiber 1xN switches to time-share the use of a network between several users. One network port will connect to the switches, with two fibers – transmit and receive. On the other side of the switches each pair of fibers will be connected to a pair of an optical transmitter and an optical receiver, aimed at one network user. This enable to begin serving high data rate network interconnect to customers in a time-shared fashion, and adjust the percentage of time used according to the needs of each customer. When the need arises, a dedicated network port could be used to direct-connect a customer for a full connection. The structure of the system having fully transparent optical transmitters and receivers allow for seamless transfer to the use of dedicated fibers between the two locations when such fibers are installed.

A construction is described where the beam transmitter and the beam receiver share the use of one MEMS mirror. Servo control of the MEMS mirror angular position may be achieved with separate servo LED source and servo optical position detector. Close loop servo control is critical to the correct operation of the transmission system.

DESCRIPTION OF THE DRAWINGS

Figure 1 shows the construction of a beam transmitter or beam receiver unit in accordance with one embodiment of the invention.

Figure 2 is a schematic drawing showing the movement of the image of the optical fiber end in accordance with one embodiment of the invention.

Figure 3 is the MEMS mirror drawn showing the mirror and package in accordance with one embodiment of the invention.

Figure 4 shows a different optical design of the beam transmitter in accordance with one embodiment of the invention.

Figure 5 is an example of a mechanism for course aiming in accordance with one embodiment of the invention.

Figure 6 is a different azimuth-elevation structure in accordance with one embodiment of the invention.

Figure 7 shows a network system using the beam transmitters and receivers described in accordance with one embodiment of the invention.



Figure 8 shows fiber amplifiers being inserted into a communication link in accordance with one embodiment of the invention.

Figure 9 shows a system where several sub networks are served by one main network in accordance with one embodiment of the invention.

Figure 10 shows the possible use of one MEMS mirror to control both the transmitted beam and the received beam in accordance with one embodiment of the invention.

Figure 11 shows the design of a MEMS mirror serving both transmission and reception in accordance with one embodiment of the invention.

Figure 12 shows a servo LED being used as a light source in accordance with one embodiment of the invention.

Figure 13 shows the servo sensor, which uses the same MEMS mirror as described in accordance with one embodiment of the invention.

Figure 14 shows an outside view of the beam transmitter and receiver unit in accordance with one embodiment of the invention.

Figure 15 shows a flattened drawing of the optical system of figure 14.

## DETAILED DESCRIPTION

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The invention comprises a method and apparatus for MEMS based over-the-air optical data transmission system. In the following description, numerous specific details are set forth to provide a more thorough description of embodiments of the invention. It will be apparent, however, to one skilled in the art, that the invention may be practiced without these specific details. In other instances, well known features have not been described in detail so as not to obscure the invention.

Figure 1 shows the construction of a beam transmitter or beam receiver unit in accordance with one embodiment of the invention. In a beam transmitter, the light that propagates in the optical fiber is exiting the fiber end in a cone. The optical fiber is a common Single Mode telecommunications fiber, with core diameter of approximately 10 microns and cladding diameter of 125 microns. The cone of light hits the MEMS mirror and is deflected towards the lens, which collimates the beam for transmission. The collimation may not be exact, as larger or smaller beam angles may be required. The mirror may be rotated in two degrees of freedom over two perpendicular axis (not shown) which are parallel to the mirror surface. The image of the optical fiber end is thus moved in space. By moving the image of the optical fiber, the beam that emerges from the lens change direction.

Figure 2 is a schematic drawing showing the movement of the image of the optical fiber end in accordance with one embodiment of the invention. Light cone emerges from the fiber core at the fiber end. This cone is reflected by the MEMS mirror. The mirror is rotate-able around the axis shown, and the second axis is not shown for clarity. When the mirror is in position A, the mirror creates an image A and the light exits in cone A. When the mirror is in position B, the mirror creates an image B and the light exits in cone B. Since image A and B are in different positions, the lens will collimate light exiting from these images in different directions. The two exiting cones have some beam wander on the lens, requiring somewhat larger lens diameter.

In figure 3, the MEMS mirror is drawn showing only the mirror and package. The package is a mechanical structure that holds and protects the MEMS mirror. The mirror package may have a window that enables hermetic sealing, not shown here for clarity. The MEMS mirror can be controlled to rotate in the horizontal and vertical axis. A detailed description of the type of MEMS mirror useful for this application may be found in "Optical Switch Demos in Cross-Connect" by David Krozier and Alan Richards, Electronic Engineering Times, May 13, 1999, p. 80 and in EP 962796A2. The MEMS mirror dimensions are reported to be approximately 3mm x 4mm. The size is larger than a typical MEMS mirror and is quite useful for the construction of the beam transmitter

unit. A smaller MEMS mirror will require the fiber to be very near to the mirror, maybe obstructing part of the beam. Also, a small mirror will create only small deviation of the position of the image of the fiber, and achieve small active angle of aiming. The reader should not, however, that the size of the MEMS mirror may vary in accordance with different embodiments of the invention.

Figure 4 shows a different optical design of the beam transmitter. The beam emerging from the fiber is collimated by an "on-axis" lens. The collimated beam is reflected by the MEMS mirror into an "eyepiece" lens. The eyepiece lens focuses the beam into a real image spot at or near the focal plane of the lens. The lens creates a collimated or nearly collimated beam for transmission. By rotating the MEMS mirror, the location of the real image can be adjusted, thereby adjusting the direction of the transmitted beam.

It is common knowledge that for any path taken by a beam of light, the reverse is also a possible path for another beam. Therefore, figures 1-4 which were described above as beam transmitters could be used to explain similar design beam receivers. A light beam arrives at the lens and being focused and directed to the fiber end by the MEMS mirror. The direction from where the fiber will accept light is controlled by the MEMS mirror. The fiber in the beam receiver could be identical to the fiber in the beam transmitter, but it may also be a common Multi Mode fiber, with core diameter of 50 or 62.5 microns and clad

diameter of 125 microns. Larger core diameter will allow relaxed aiming accuracy, but will limit the data rate if the fiber is long, due to modal dispersion.

A pair of units, a beam transmitter and a beam receiver, together creates an optical link. The distance between beam transmitter and beam receiver could be several kilometers. For two-way communications, light can be made to propagate in the fibers in both directions simultaneously. Alternatively, two pairs of units can be used to create a full duplex link.

The beam steering by the MEMS mirror is limited in angle. Only a few degrees of angular deviation are typically possible. In some designs, only a fraction of a degree of adjustment is possible. Therefore, a mechanism for course aiming is required, that is capable of aiming in 360 degrees in azimuth and approximately  $\pm 45$  degrees in elevation. Figure 5 is an example of such mechanism. The beam transmitter (or receiver) is mounted onto a mount, with a motor that controls the horizontal axis of rotation of the beam transmitter/receiver. This motor enables the movement of the beam in elevation. The exact design of the motor and movement mechanism are not shown since it is a common art. The mount is attached to the base with similar drive, which enables rotation around the vertical axis, for adjusting the beam direction in azimuth. The motors are capable of aiming the beam generally to the target, but are neither fast nor accurate enough to track the building movements.

Figure 6 is a different azimuth – elevation structure. The beam transmitter or receiver is mounted on a base facing up. A large folding mirror directs the beam in a general horizontal direction. The beam transmitter (receiver) and the folding mirror rotate around vertical axis for azimuth control. It is possible that only the folding mirror will rotate to achieve azimuth control. The mirror aims the beam in elevation by rotating around a horizontal axis. Again, the motor drive is not shown since it is common art.

Figure 7 shows a network system using the beam transmitters and receivers described above. The main network needs to interconnect with the sub network. The main network and the sub network are located in different buildings with free line-of-sight between them. Also possible is interconnect between different floors of the same building by sending the beams vertically. A network element is attached to the main network, such as a switch, router and the like. A port in the network element is connected to the beam transmitter and receiver with a pair of fibers. A laser or LED transmitter and a PIN or avalanche photodiode detector at the network element performs the light generation and detection respectively, commonly marked TX and RX. The beam transmitter and receiver are mounted on the roof or in a window, aimed at the beam transmitter and receiver which are connected to the sub network with fibers. When the beam units are correctly aimed at each other, light from the TX unit at each

network element is passing via the fiber to the beam transmitter, over the air to the beam receiver and to the RX unit at the other network element. A full duplex communication is established.

Since the network elements sees standard fibers attachments, it is very simple to connect direct point-to-point optical fibers when available, replacing the over-the-air link. This feature allows for seamless growth of the network.

Optical transmission from the TX unit to the RX unit will suffer losses, due to loss in the fibers, optical aberrations and diffraction in the beam transmitter and receiver, the receiver aperture being smaller in diameter than the beam generated by the beam transmitter, inaccuracies in the aiming servo mechanism for both transmitter and receiver, optical absorption and scattering in the atmosphere, etc. In common 2.5 Gbps transmission equipment such loss is allowed to reach 20-30dB, i.e. only 1/100 to 1/1000 of the light transmitted by the laser should arrive at the detector to achieve low error rate transmission. If the link loss is excessive, fiber amplifiers could be inserted in the link as shown in figure 8. The optical fiber amplifiers that are commonly used are Erbium Doped Fiber Amplifiers (EDFA). An amplifier may be inserted into the link after the laser to boost the transmitter power, or before the receiver to increase the received optical power, or in both locations. If the high loss is a phenomenon



related only to fog condition, the amplifiers may be inserted actively when the bit error rate deteriorates.

Figure 9 shows a system where several sub networks are served by one main network.  $1 \times N$  fiber optics switch is attached to the TX in the main network. The switch is serving light to one of the beam transmitters at a time. A second switch is connected to the RX. Each sub network operates for a short time, and then is disconnected for a longer time. For example, the switching time may be 5 mS and each sub network could be served for 100 mS at a time. If there are 5 sub networks, there will be a gap of 425 mS between connections for any specific sub network. Some messages may be delayed, but this may be tolerated. If the link loss is different to different sub networks, the gain of the optical amplifier may be adjusted to each sub network differently. Fast AGC is required on all the RX units. This construction enables the installation of standard transmission equipment, for example Gigabit Ethernet, in all the network elements, even when the communications needs is lower, and adjusting the main network connect time to each sub network according to the needs. An advantage is the use of only two optical amplifiers, which are expensive. Another advantage is that the connectivity to each sub network may be adjusted without the need for a physical equipment change, and remotely. The user of the sub network may be charged for network services according to the average data rate he uses. Only when a sub network needs full connectivity at the main network data rate, then

this sub network could be assigned a port in the main network and direct connection instead via the fiber switches.

Figure 10 shows the possible use of one MEMS mirror to control both the transmitted beam and the received beam. The transmit fiber is shown having Numerical Aperture (NA) of 0.1, which is common for Single Mode fibers, and creates an opening of the beam at about 5.7 degrees from the axis. The beam reflects from the MEMS mirror and is aimed at the transmit lens via a fixe mirror. The receive fiber is shown having NA of 0.26, which is common for Multi Mode fibers with core diameter of 62.5 microns. The received beam will have radius of about 15 degrees. Since it is intended to use the same area of the MEMS mirror for both transmission and reception, the transmit and receive cones can not have parallel axis at the MEMS mirror. The fixed lens is used, therefore, to make the transmit and receive beams parallel outside of this combined beam transmitter and receiver.

Figure 11 shows the design of a MEMS mirror serving both transmission and reception, where the beams at the MEMS mirror are substantially collimated. The description of each optical path, for transmission and reception, is essentially the same as described for figure 4.

The operation of the atmospheric optical link depends critically on the correct aim of the transmit and receive beams. A servo control must be employed to aim the beams. The servo system should have a different mechanism to align the beams than the data beams, and many different ways are known and described in the prior art. We need, however, a mechanism that makes use of the positioning of the same MEMS mirror as the transmit and receive beams. The essential parts of such a servo mechanism are shown in figures 12 and 13. In figure 12, a servo LED is used as the light source. Laser could also be used. The servo LED emits light modulated at relatively low speed, enabling detection with low received power. The servo LED lens creates a wide cone of light from the light emitted by the servo LED. This cone may be several degrees wide, so the aiming is very simple and the amount of detected radiation is not sensitive to small movements of this beam. Figure 13 shows the servo sensor, which uses the same MEMS mirror as described before. The sensor uses optical position detector, which is a common art and includes Silicon diode with several outputs. The electrical signals outputted from the detector are sensitive to the intensity of the optical signal and to the exact location of the optical signal on the detector. The electrical signals indicate if the MEMS mirror is aiming the servo sensor beam directly at the opposing servo LED. If there is an error in aiming, the electrical signal outputted from the detector indicates the direction and magnitude of the error. The servo system will then adjust the MEMS mirror correctly.

Figure 14 shows the outside view of the beam transmitter and receiver unit. In figure 15 a flattened drawing of the optical system of figure 14 is shown. The optical beams are shown by the central beam only, for clarity. One MEMS mirror is used to control three beams concurrently.

Thus, a method and apparatus for MEMS based over-the-air optical data transmission system has been described. However, the claims and the full scope of their equivalents describe the invention.